(sub)-PeV gamma-ray astronomy with *CARPET*

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for the Carpet-2 Collaboration

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(sub)-PeV GAMMA-RAY ASTRONOMY

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INR, Baksan & Moscow

Acknowledgements

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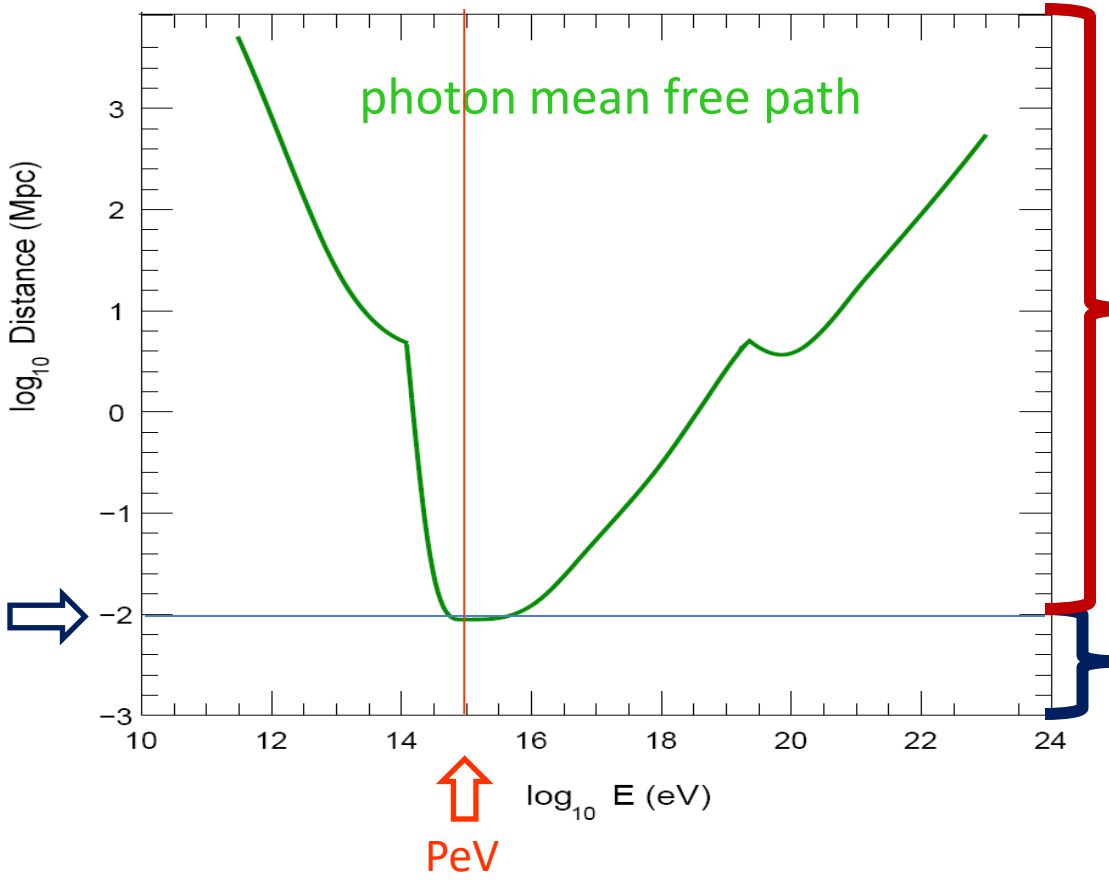
Fate of PeV photons

Pair production on background radiation

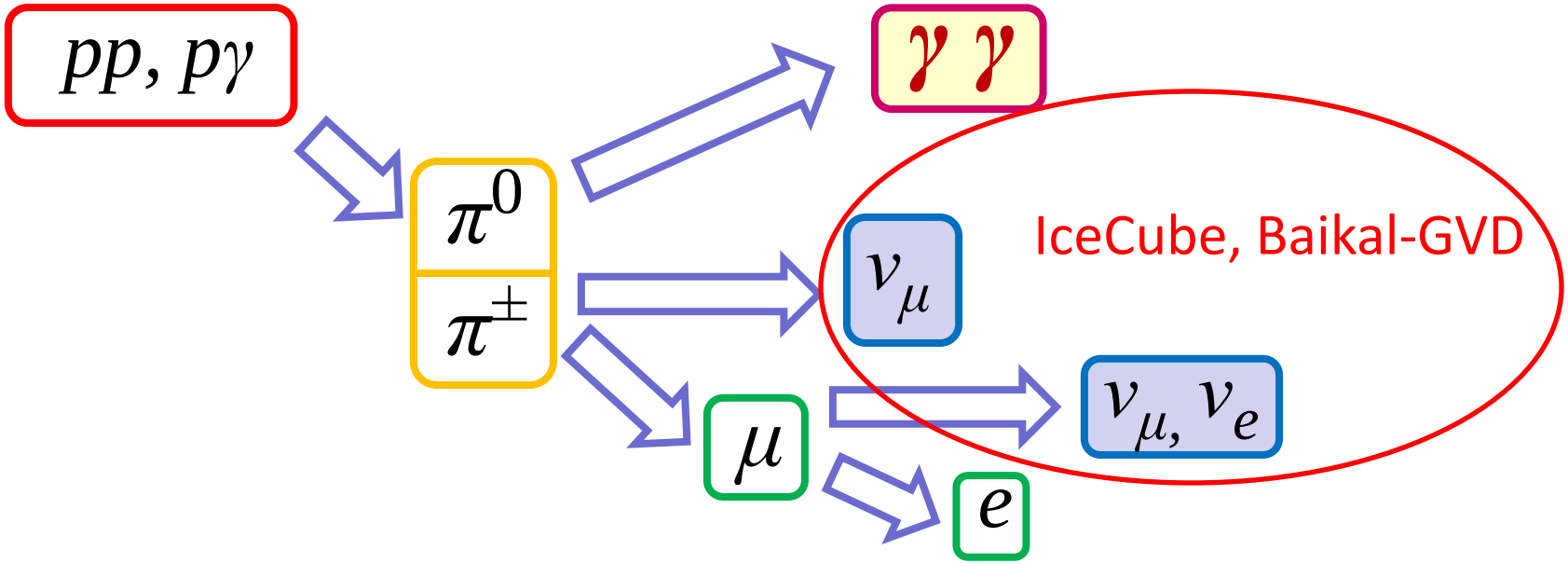


~ 10 kpc ⇨

Extragalactic PeV photons cascade, degrade in energy, contribute to the diffuse ~(1-100) GeV background

Galactic PeV photons reach the observer

Why to expect any PeV photons?



✓ High-energy (E>100 TeV) neutrinos are accompanied by HE photons (if from π mesons)

✓ Cascades on CMB ⇨ strong suppression for extragalactic sources

⇩

Searches for the HE photons distinguish between galactic and extragalactic origins of high-energy astrophysical neutrinos

How to find PeV photons?

- PeV photons produce extensive air showers in the atmosphere
- Low fluxes, need an EAS array like those used for cosmic-ray searches
- Need to separate primary photons from cosmic-ray protons/nuclei
- The best separation strategy: muons

γ-ray air showers are **muon-poor**

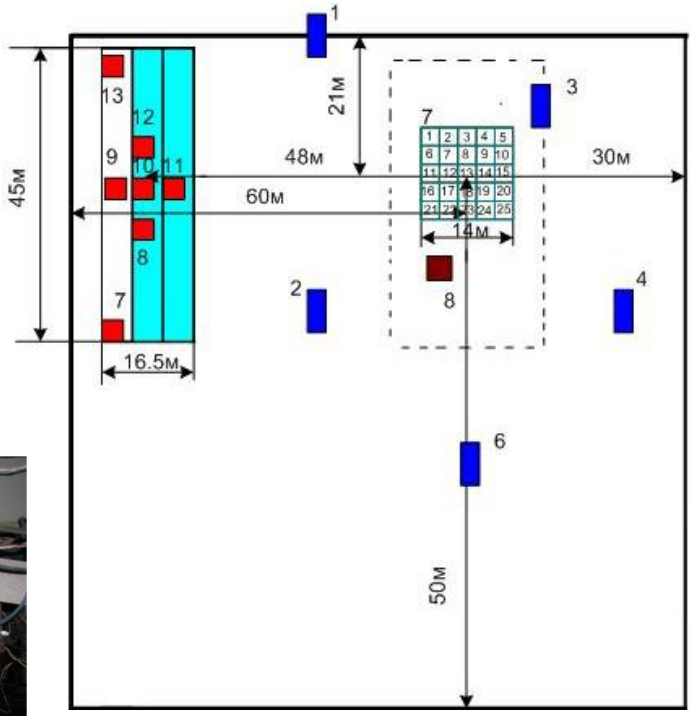
EAS+muon detector installation

Carpet-2: air-shower array @ Baksan Neutrino Observatory

EAS+muon detector installation

Carpet-2: air-shower array @ Baksan Neutrino Observatory

- ✓ surface scintillator detector
- ✓ 175 m^2 muon detector (E_μ>1 GeV)
- ✓ ~10 years of data

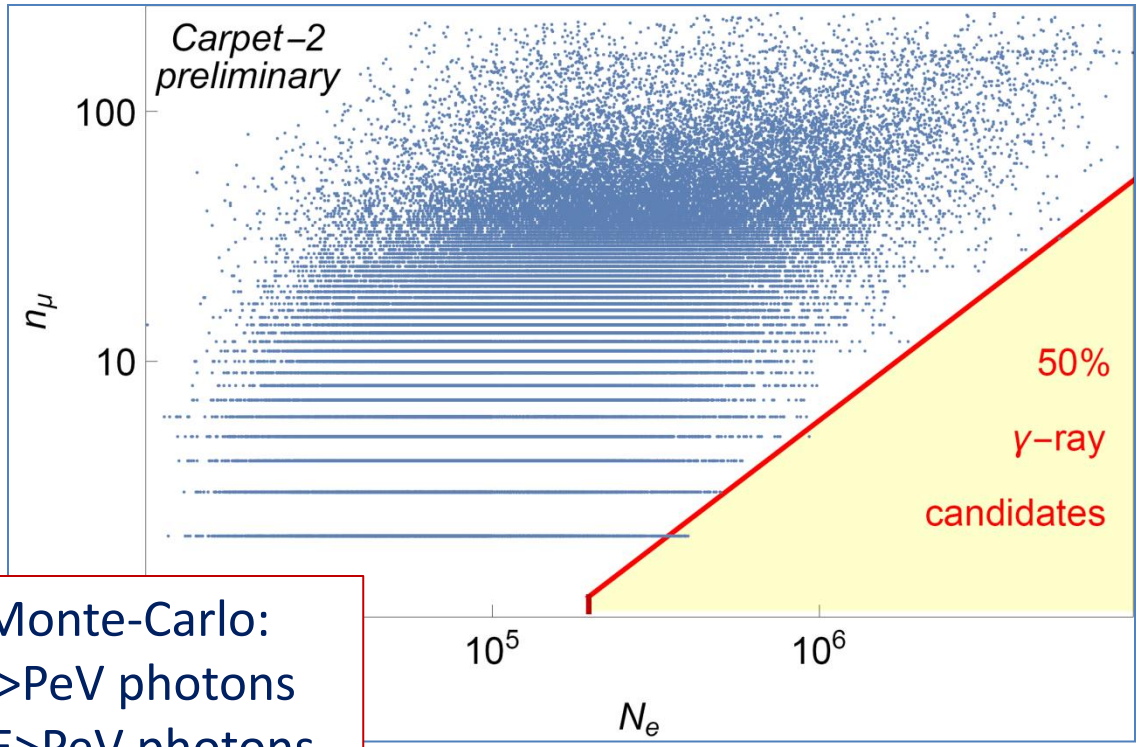


Search for PeV photons with Carpet

γ-ray showers are **muon-poor**

Dataset I
(target E>1 PeV)

- 1999-2011
- 3080 days live
- 115821 events
- 35 photon candidates



photon candidate cuts from Monte-Carlo:
✓ min N_e to include 90% of E>PeV photons
✓ max n_μ/N_e to include ½ of E>PeV photons

Search for PeV photons with Carpet

γ-ray showers are **muon-poor**

Dataset I
(target E>1 PeV)

- 1999-2011
- 3080 days live
- 115821 events
- 35 photon candidates

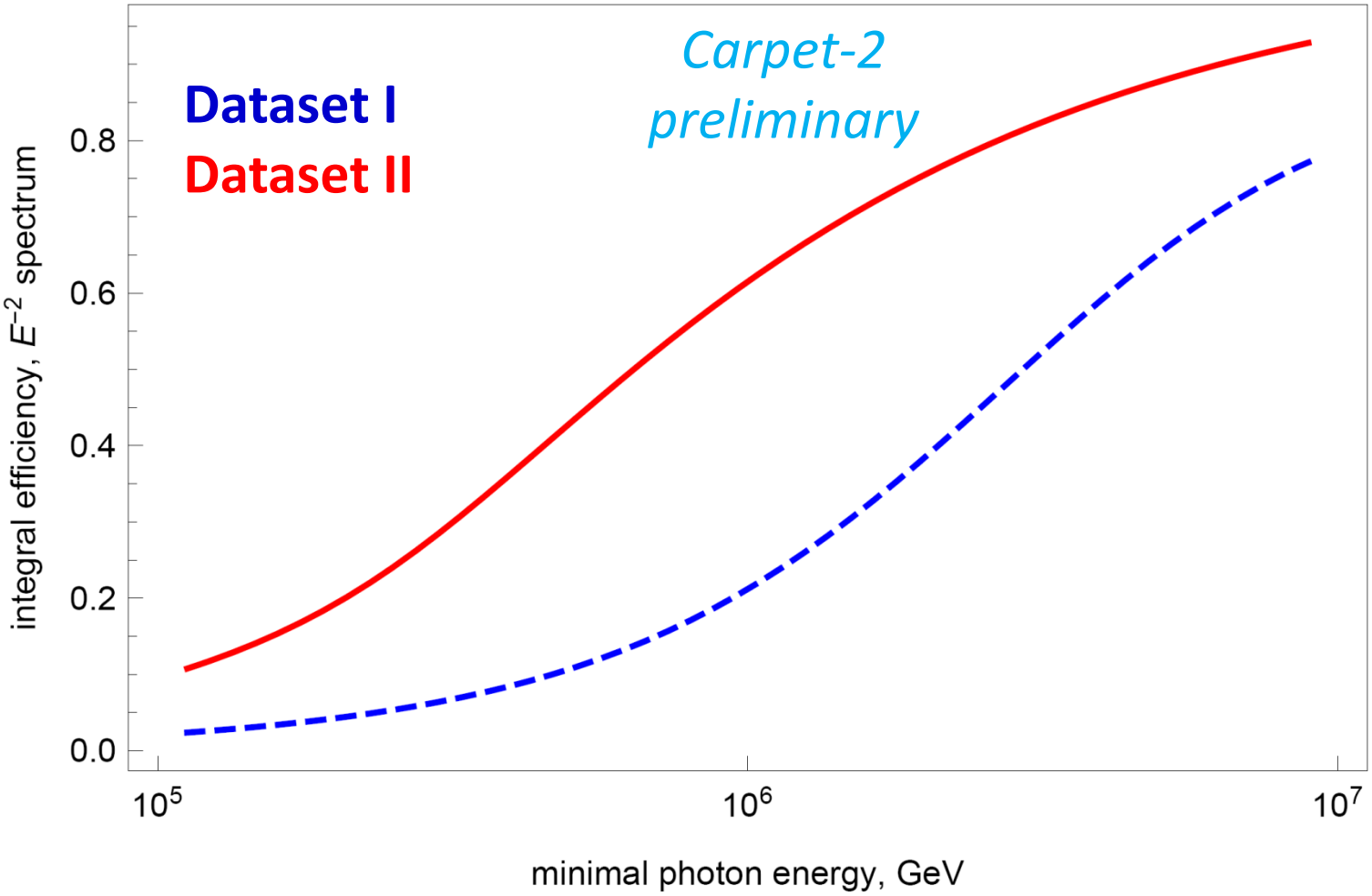
Dataset II
(target E>0.3 PeV)

- 2018-2019
- 342 days live
- 25876 events
- 386 photon candidates

photon candidate cuts from Monte-Carlo:
✓ min N_e to include 90% of E>PeV photons
✓ max n_μ/N_e to include ½ of E>PeV photons

Search for PeV photons with Carpet

γ-ray efficiency

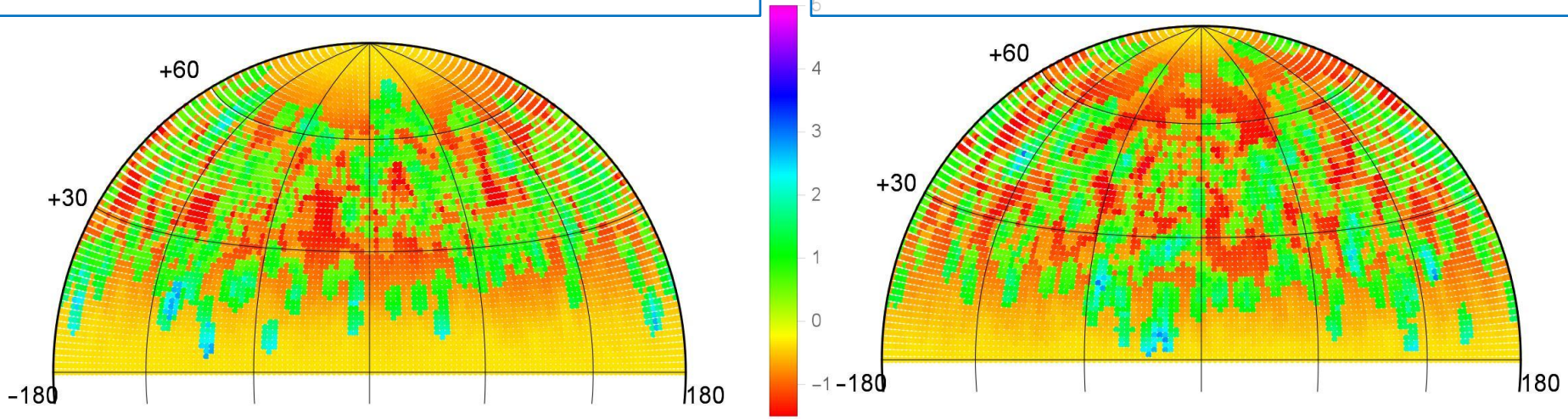


Search for PeV photons with Carpet, results

- first ever skymaps of excesses of E>300 TeV photon candidates

Dataset I: “cosmic-ray friendly”,
E>1 PeV

Dataset II: “gamma-ray friendly”,
E>0.3 PeV



1999-2011

Carpet-2 preliminary

2018-2019

Carpet-2, ICRC 2019 [arXiv:1907.10893]

Search for PeV photons with Carpet, results

• point sources:
correlate arrival direction of photon candidates with source positions in the sky

- pre-defined list of 4 sources
- stacked arrival directions of IceCube events
- IceCube alerts (direction+time)

• diffuse flux:
need to be careful with hadronic backgrounds, more Monte-Carlo to come

Stacked arrival directions of IceCube events

ID	R.A.	DEC	Error
HES13	67.9	+40.3	1.2
HES38	93.34	+13.98	1.2
HES47	209.36	+67.38	1.2
HES62	187.9	+13.3	1.3
HES63	160.0	+6.5	1.2
HES82	240.9	+9.4	1.2
DIF2	298.21	+11.74	0.45
DIF4	141.25	+47.80	0.43
DIF5	306.96	+21.00	2.13
DIF7	266.29	+13.40	0.54
DIF8	331.08	+11.09	0.55
DIF10	285.95	+3.15	1.09
DIF12	235.13	+20.30	1.71
DIF13	272.22	+35.55	0.85
DIF16	36.65	+19.10	1.96
DIF17	198.74	+31.96	0.96
DIF20	169.61	+28.04	0.85
DIF23	32.94	+10.22	0.52
DIF24	293.29	+32.82	0.56
DIF25	349.39	+18.05	2.70
DIF27	110.63	+11.42	0.37
DIF28	100.48	+4.56	1.08
DIF29	91.60	+12.18	0.40
DIF30	325.5	+26.1	1.62
DIF31	328.4	+06.00	0.55
DIF32	134.0	+28.00	0.45
DIF33	197.6	+19.9	2.33
DIF34	76.3	+12.6	0.66
DIF35	15.6	+15.6	0.53
EHE3	46,58	+14.98	0.78
EHE5	77.43	+5.72	0.83
EHE6	340.0	+7.40	0.47
AHES1	240.57	+9.34	0.60
AHES4	40.83	+12.56	0.88

34 IceCube tracks
in the Carpet field of view

- expected γ candidates: 38.1
- observed γ candidates: 34

stacked flux limit:
$<1.4\times10^{-14}$ cm^{-2} s^{-1}
(90% CL)

Carpet-2, JETPL 2018 [arXiv:1812.02662]

Direction+time: IceCube alerts

Only one IceCube track in the (live) Carpet field of view

16/12/10	UT 20:07:16	RA=46,58°	DEC=+14,98°

- ±3 days, observed γ candidates: 0

  E>PeV γ fluence limit: <0.2 GeV cm^{-2} (90% CL, E^{-2})

Carpet-2, JETPL 2018 [arXiv:1812.02662]

Predefined point sources

Carpet-2 preliminary

Source	Dataset I: $E_\gamma > 1$ PeV			Dataset II: $E_\gamma > 0.3$ PeV		
name	expected	observed	flux, $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	expected	observed	flux, $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Crab	0.69	0	$< 4.69 \times 10^{-13}$	0.95	4	$< 1.57 \times 10^{-11}$
Cyg X-3	1.75	2	$< 3.00 \times 10^{-13}$	2.08	1	$< 1.83 \times 10^{-12}$
Mrk 421	1.59	5	$< 6.32 \times 10^{-13}$	1.90	4	$< 5.45 \times 10^{-12}$
Mrk 501	1.70	0	$< 8.8 \times 10^{-14}$	1.93	1	$< 2.00 \times 10^{-12}$

Table 1: Results of the photon search from four predefined sources. Flux upper limits are 95% CL.

Carpet-2, ICRC 2019 [arXiv:1907.10893]

Search for (sub)-PeV photons with *Carpet-2*, final results to come very soon:

- diffuse flux (expected sensitivity similar to CASA-MIA with our old data)
- Galactic plane
- various dark-matter searches:
  - Galatic dipole
  - dwarfs
  - the Sun (weird DM models)
- unknown point sources (clustering) - new classes? DM clumps?...

- point sources:

correlate arrival direction of photon candidates with source positions in the sky

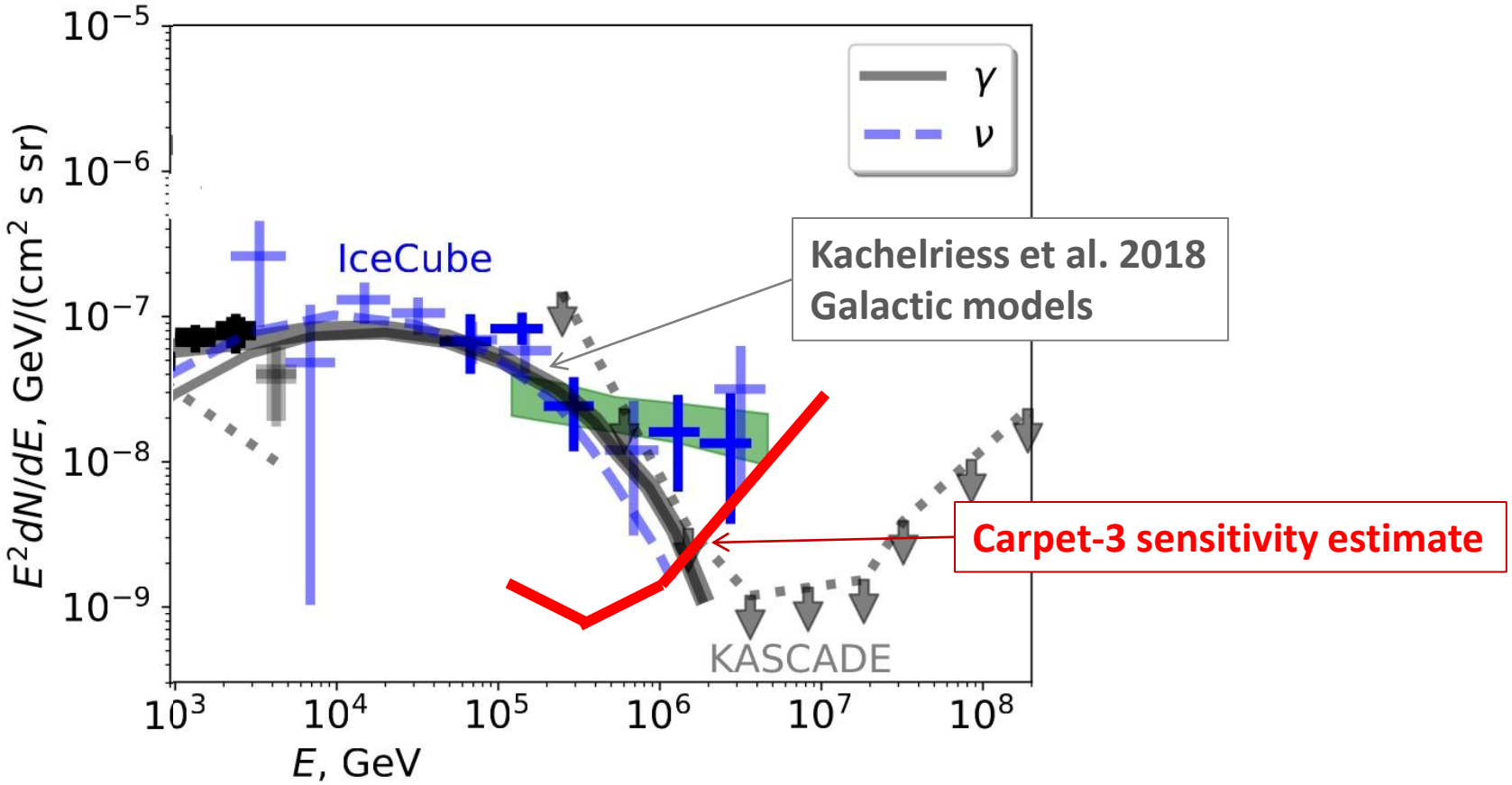
  - pre-defined list of 4 sources, continued monitoring
  - HAWC E>0.1 PeV sources
  - stacked arrival directions of IceCube events, updated
  - IceCube alerts (direction+time), updated

Upgrade to Carpet-3

- 410 m^2 muon detector (versus 175 m^2)
- increased surface area
- new muon detector starts data taking (first light, September 25, 2019)

Target: diffuse photons above 100 TeV

Expected sensitivity to diffuse photons



Conclusions

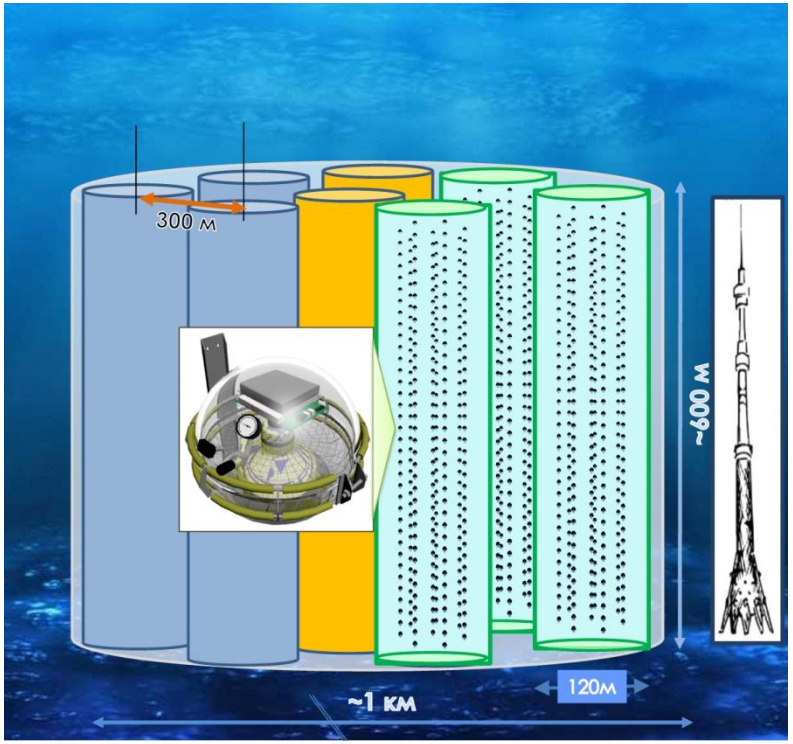
- motivation to search for PeV photons
  - ✓IceCube+Baikal neutrinos, origin unclear
- first ever results for E>0.3 PeV photons
  - ✓ association with IceCube events
  - ✓ selected point sources (Crab, Cyg X-3, Mrk 501, Mrk 421)
  - ✓ excess skymaps
  - ✓ more to come
- Carpet-3 upgrade and diffuse fluxes to come soon!

STAY TUNED!

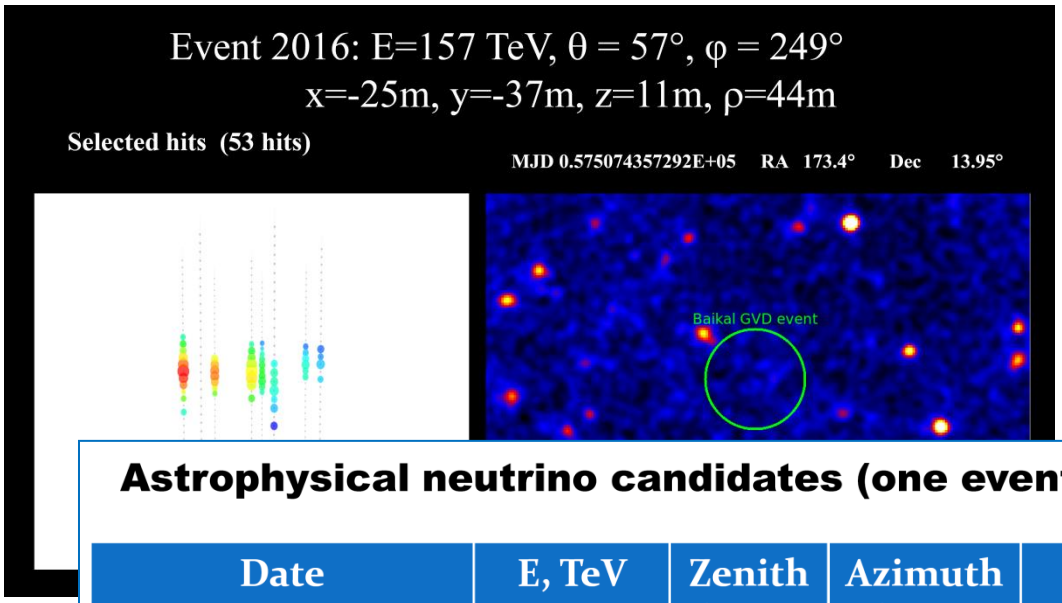
Backup slides

Tests of IceCube results: Baikal-GVD

- Baikal-GVD: ~ IceCube by 2021, 5/8 taking data
- Northern hemisphere
- fresh water – better angular resolution than ice



Tests of IceCube results: Baikal-GVD



Baikal-GVD, ICRC-2019

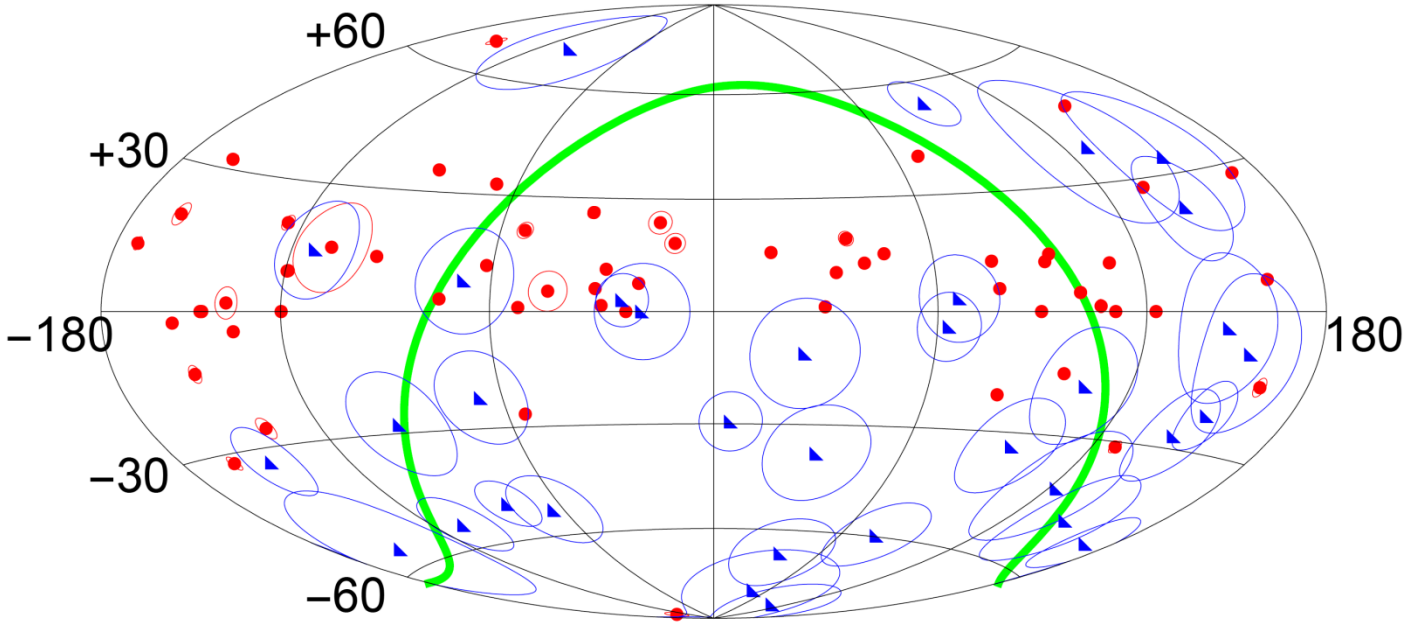
Astrophysical neutrino candidates (one event was selected in 2019 data)

Date	E, TeV	Zenith degree	Azimuth degree	Ra	Dec	T_{UNIX}
16.11.2016	107.2	56	131	139.5	5.6	1447637711
29.04.2016	157	57	249	173.4	14.0	1461925647
21.08.2018	153	49	57	231.7	49.1	1534868736
24.10.2018	107	69	112	41.3	0.7	1540416000
15.02.2019	339	67	350	68.4	61.9	1550278144

Number of cascade events (5 above 100 TeV) –
in agreement with the IceCube flux

IceCube: E>60 TeV neutrinos

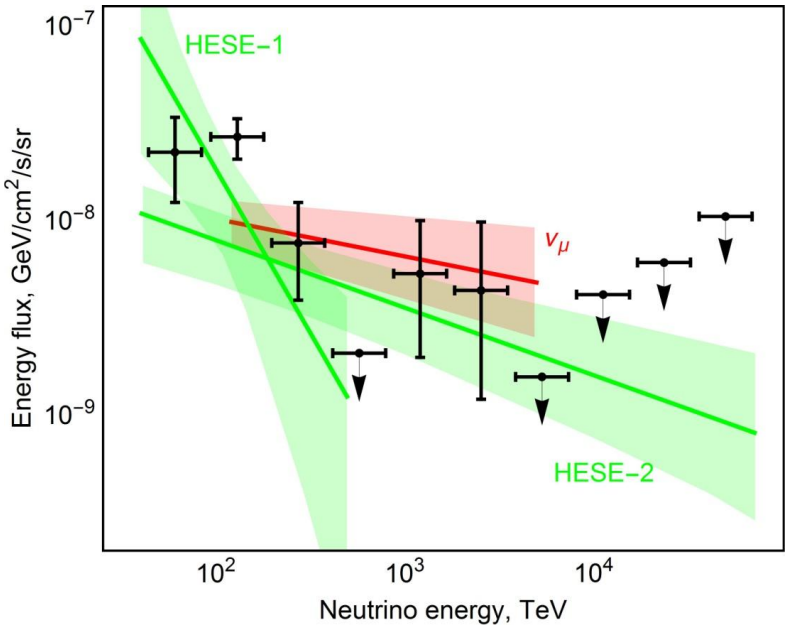
- +/- isotropic flux of high-energy (60 TeV – a few PeV) neutrinos
- no Galactic disk excess
- no clusters (no excess of doublets)



Plotted with the data from Padovani et al. [arXiv:1804.01386]
All published IceCube events by April 2018

IceCube: E>60 TeV neutrinos

• a certain disagreement in spectra below and above ~200 TeV (two components? North-South difference?)



Plotted with the data from Ahlers, Halzen [arXiv:1805.11112]
IceCube 6 years

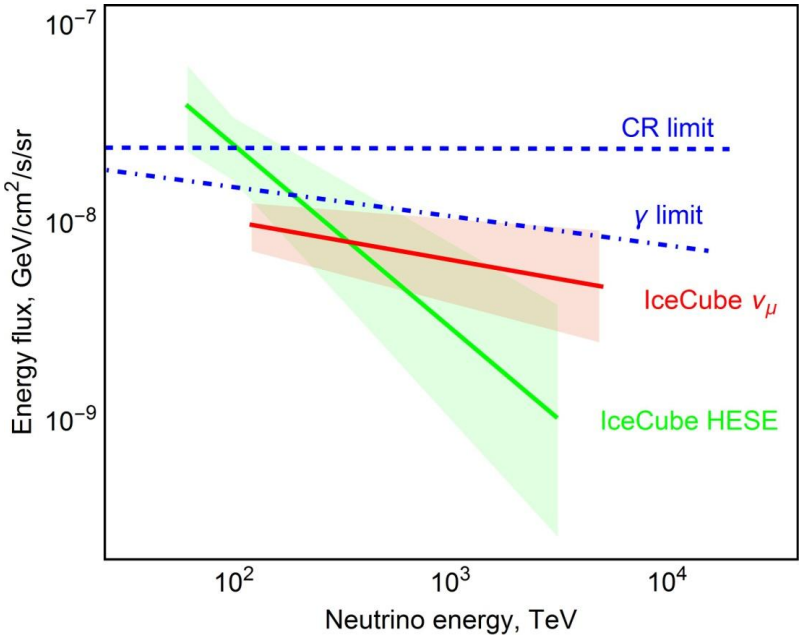
IceCube: E>60 TeV neutrinos

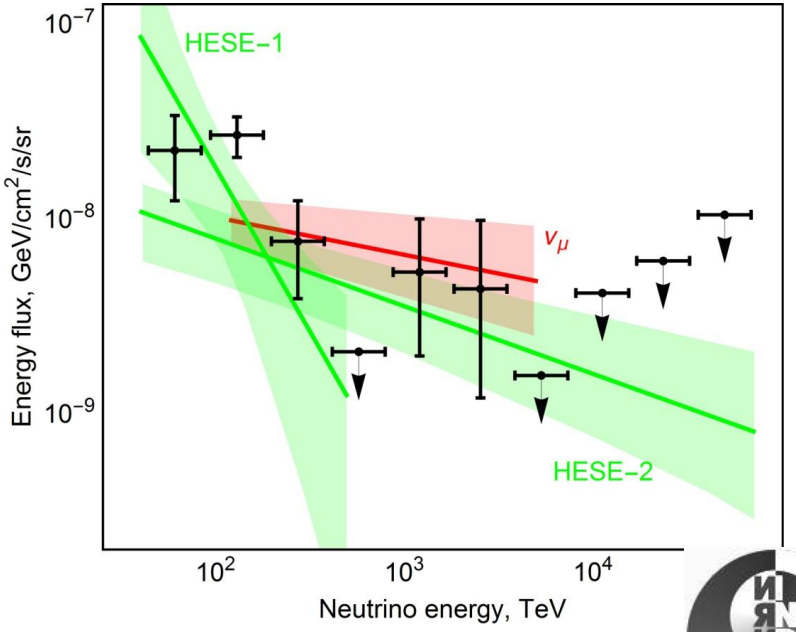
- excitement with a 3-sigma (?) coincidence with a blasar flare
- <7% of events can come from such blazars (tunable to 15%)

- 1 event coincided, 44 – not…
- no clusters of events
- gamma-ray constraints

IceCube

- +/- isotropic flux of high-energy (60 TeV – a few PeV) neutrinos
- no Galactic disk excess
- if extragalactic origin, then problems with the Fermi-LAT diffuse gamma-ray background
- excitement with a 3-sigma coincidence with a blasar flare, but <7% (tunable to ~15%) of the flux from blazars
- a certain disagreement in spectra below and above ~200 TeV (two components?)

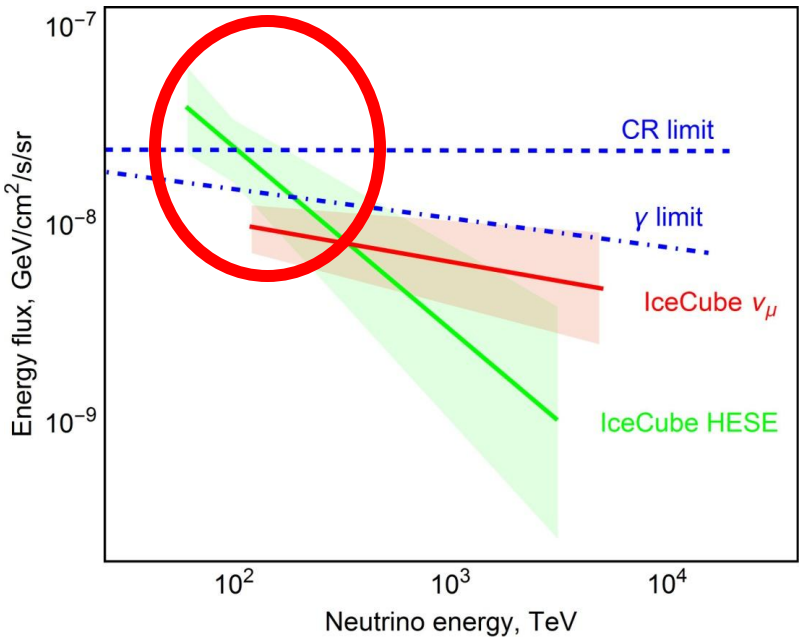


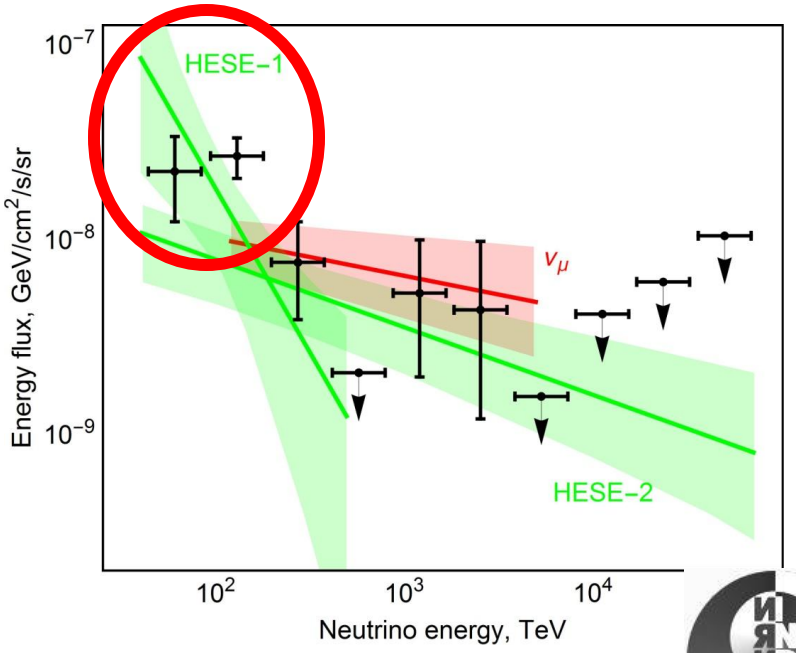


IceCube

- the low-energy component should be Galactic to avoid Fermi-LAT constraints!

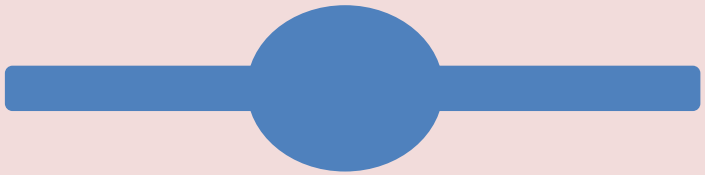
- diffuse flux:
  - ✓ dark matter? heavy dark matter decays
  - ✓ cosmic-ray interctions with circumgalactic gas
  - ✓ local source? “local bubble”
- numerous point sources? DM clumps?





Isotropic Galactic neutrinos?

- the low-energy component should be Galactic to avoid Fermi-LAT constraints!



Isotropic Galactic neutrinos?

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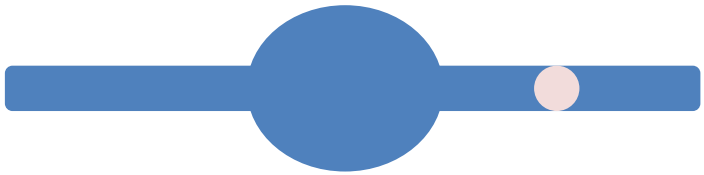
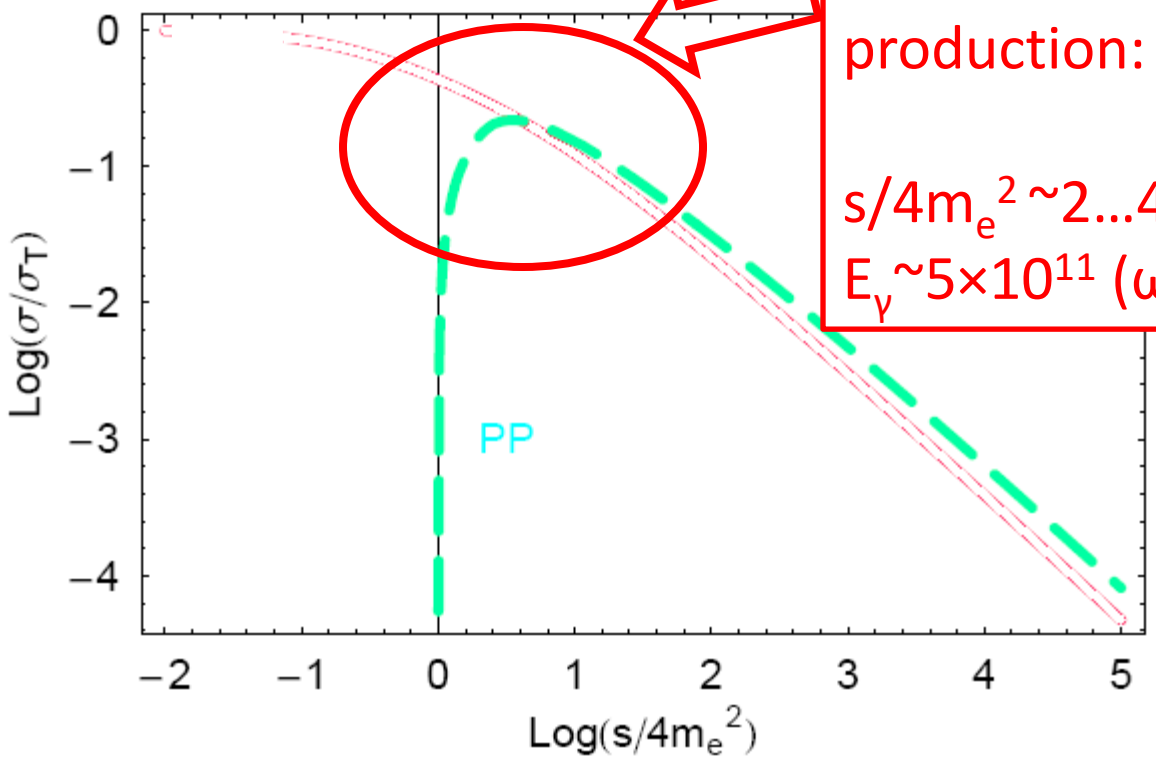


Photon cascades

Pair production on background radiation

Nikishov 1962

pair-production cross section (PP):



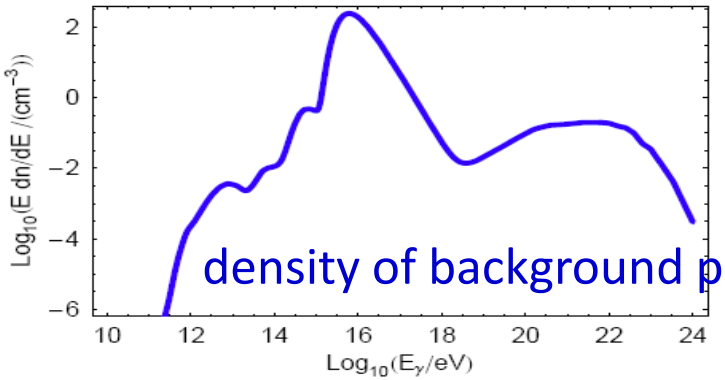
the most intense pair production:

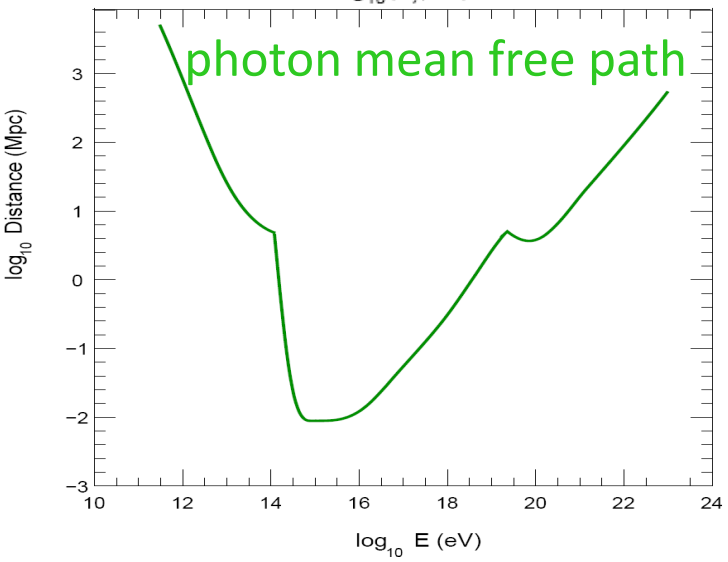
$s/4m_e^2 \sim 2...4$

$E_\gamma \sim 5\times10^{11}\ (\omega/eV)^{-1}\ eV$

Photon cascades

Pair production on background radiation

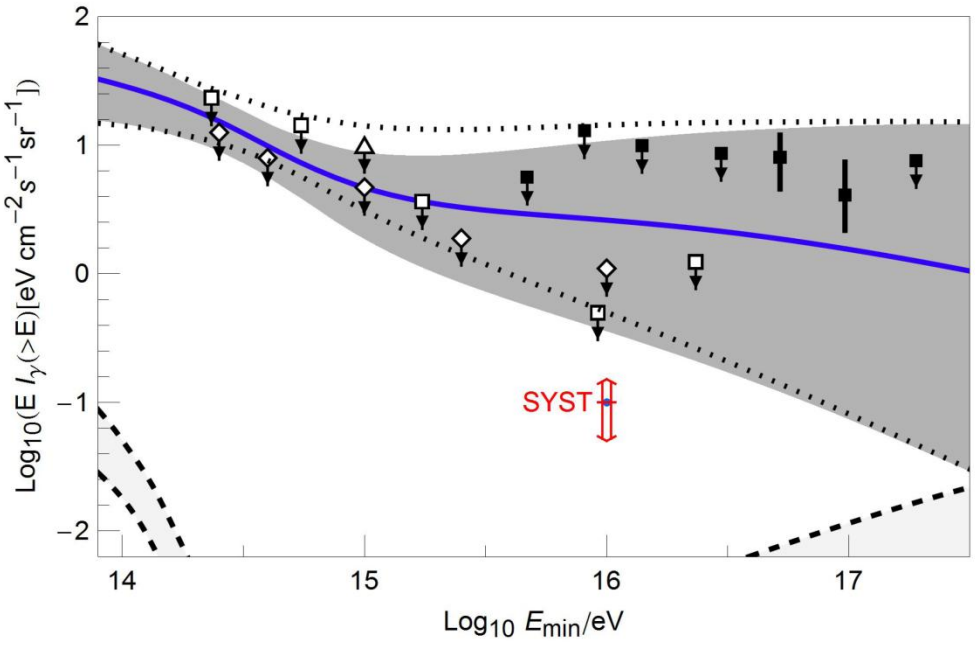




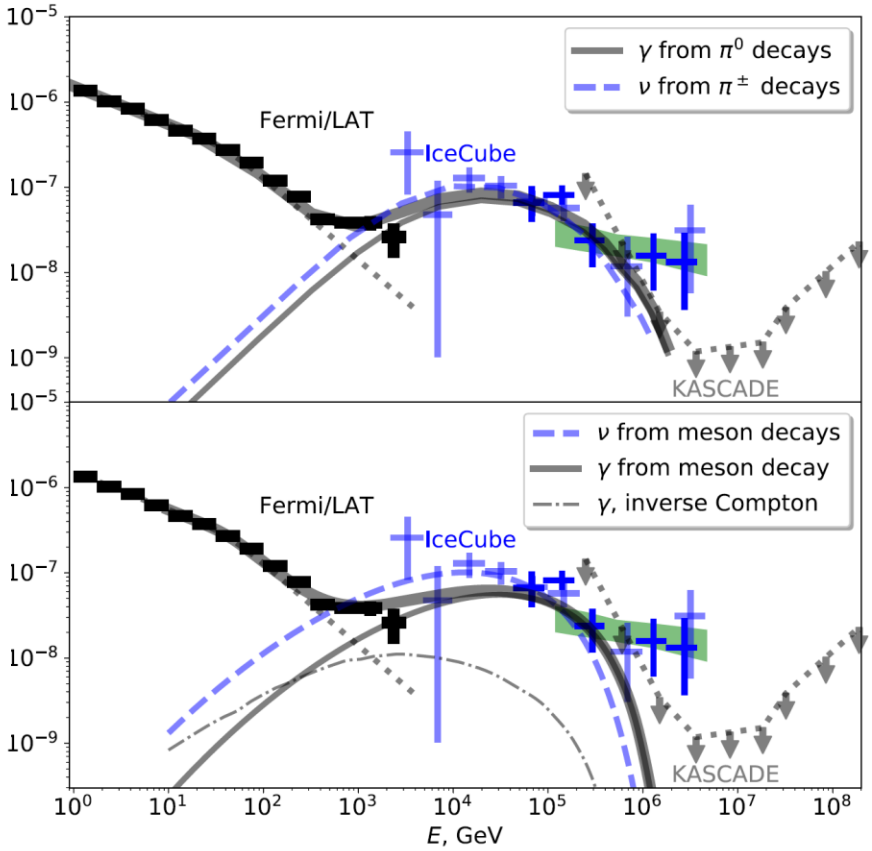
$E_\gamma \sim 5\times10^{11}\ (\omega/eV)^{-1}\ eV$

PeV photons produce pairs on CMB!

Gamma-ray predictions



Kalashev, ST 2014



Kachelriess, Neronov, Semikoz 2018

Baksan Neutrino Observatory, a branch of INR RAS

Baksan Neutrino Observatory, a branch of INR RAS

- SN 1987A neutrinos detected with BUST
- solar pp neutrinos detected with SAGE
- jets with high p_T – Carpet before CERN SPS
- lunar soil isotope analysis in low-background labs

past

- BEST – eV sterile neutrino search with a neutrino source and gallium, data taking completed on October 14
- Carpet-2 PeV gamma rays + Carpet-3 starts data taking this month
- BUST still waiting for a SN…
- ultra-low-background labs, axion search etc.

present

- New Baksan Neutrino Telescope project, 10xBorexino or 1xARGO:
  - ✓ solar CNO neutrinos
  - ✓ geoneutrinos
  - ✓ diffuse supernova neutrino background

future